APPLICATION DEVELOPMENT

In future space missions, thousands of tiny craft will cooperate to explore the solar system. Providing the required autonomy will take systems and software where no one has gone before.

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NASA's Swarm Missions: The Challenge of Building Autonomous Software

The days of watching a massive manned cylinder thrust spectacularly off a platform into space might rapidly become ancient history when the National Aeronautics and Space Administration (NASA) introduces its new millenium mission class. Motivated by the need to gather more data than is possible with a single spacecraft, scientists have developed a new class of missions based on the efficiency and cooperative nature of a hive culture. The missions, aptly dubbed *nanoswarm* will be little more than mechanized colonies cooperating in their exploration of the solar system. Each swarm mission can have hundreds or even thousands of cooperating intelligent spacecraft that work in teams. The spacecraft must operate independently for long periods both in teams and individually, as well as have autonomic properties—self-healing, -configuring, -optimizing, and -protecting—to survive the harsh space environment.

One swarm mission under concept development for 2020 to 2030 is the Autonomous Nano Technology Swarm (ANTS), in which a thousand picospacecraft, each weighing less than three pounds, will work cooperatively to explore the asteroid belt. Some spacecraft will form teams to catalog asteroid properties, such as mass, density, morphology, and chemical composition, using their respective miniature scientific instruments. Others will communicate with the data gatherers and send updates to mission elements on Earth.

For software and systems development, this is uncharted territory that calls for revolutionary techniques.

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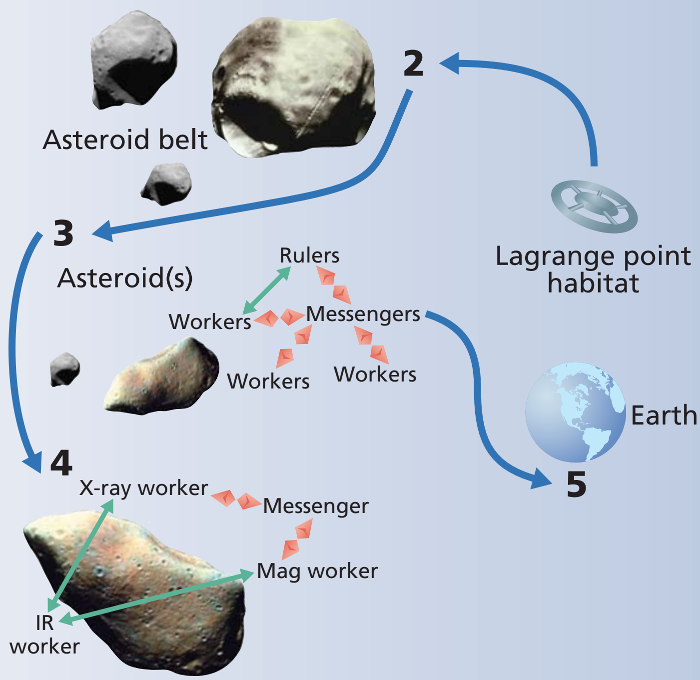
INSIDE A SWARM

Figure 1 gives an ANTS overview. A transport spacecraft launched from Earth toward the asteroid belt will carry a laboratory that will assemble the tiny spacecraft. Once it reaches a certain point in space where gravity forces are balanced, the transport will release the assembled swarm, which will head for the asteroid belt. As Figure 2 shows, each spacecraft has a solar sail, which lets it rely primarily on power from the sun, using only tiny thrusters to navigate independently. Each spacecraft also has onboard computation, artificial intelligence, and heuristics systems for control at the individual and team levels. Spacecraft use low bandwidth to communicate within the swarm and high bandwidth for data transfer back to Earth.

As both Figures 1 and 2 show, teams consist of spacecraft from three classes of spacecraft within the swarm, and members in each class combine in certain ways to form teams that explore particular asteroids. *Workers*, up to 80 percent of the

Figure 1. ANTS mission overview.



(1) When a transport ship carrying a spacecraft-manufacturing laboratory reaches a stable Lagrangian (a point in space where gravitational forces on small objects, such as spacecraft, become negligible), it builds three classes of spacecraft—workers, messengers, and rulers—and releases them to explore the asteroid belt. (2) Each spacecraft propels itself using a solar sail aided by small thrusters. (3) Once at the belt, spacecraft combine to form teams that explore individual asteroids or (4) fly by asteroids giving rudimentary data that is used to decide if the asteroid is worth exploring in depth. (5) Meanwhile, messengers continually send updates and data to Earth. Because the spacecraft must survive on their own, the challenge is how to make teams autonomous.

swarm, bear the instruments and gather data. Instruments can include a magnetometer, *x*-ray, gamma-ray, visible/infrared, or neutral mass spectrometers. Each worker gathers only its assigned data types. *Rulers* coordinate data gathering through the use of rules about what asteroid types and data are of interest. *Messengers* coordinate communications among the workers, rulers, and mission elements on Earth. Messengers, for example, can alert NASA to send replacement spacecraft from Earth or spacecraft with additional instruments.

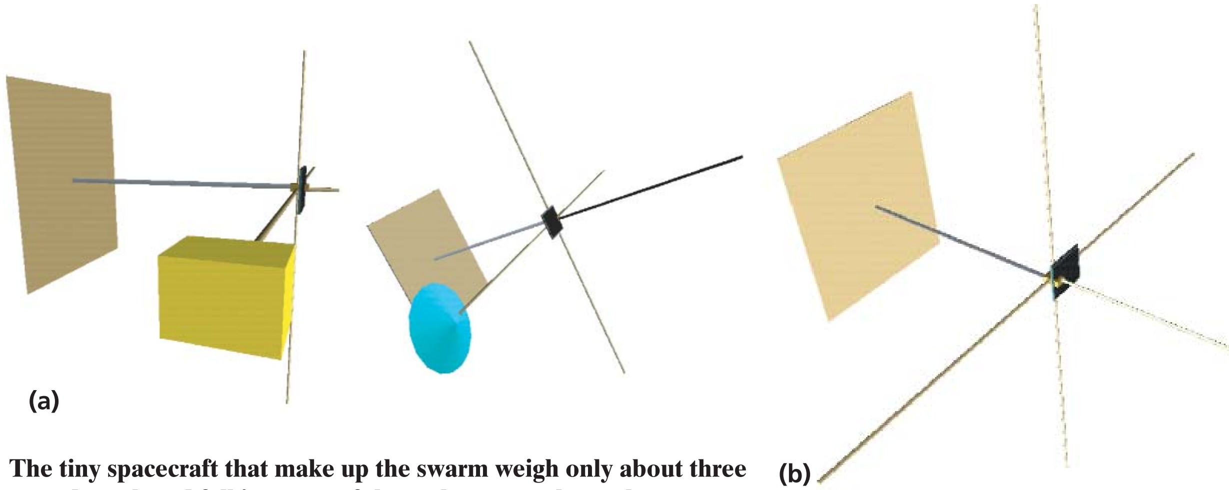
Figure 3 depicts the flow of activity as teams gather and exchange data and send it back to Earth. A single ANTS spacecraft can also survey an asteroid in a flyby, sending rudimentary data to the ruler, which then decides if the asteroid warrants further investigation using a team. The ruler chooses team members according to the instruments they carry.

Because NASA envisions the mission to operate in the same manner as a natural swarm culture, many operational scenarios are possible. In one, a worker using an imaging device finds an asteroid and after consulting its selection criteria and using heuristic reasoning, the worker determines that the asteroid merits further investigation. After the worker notifies its associated ruler, the ruler arranges for additional workers to travel to the asteroid with an expanded repertoire of instruments to gather more complete information. In effect, the spacecraft have formed a team and must now choose a team leader. The leader will be the spacecraft that contains models of the types of experiments or measures the team wants to perform. The leader relays parts of this model to the team workers, which then take measurements of asteroids using whatever type of instrument they have until something matches the goal the leader sent. The workers gather the required information and send it to the team leader, which integrates it and returns it to the ruler that formed the team in the first place. The ruler might then integrate this new information with information from previous asteroid explorations and use a messenger to carry the information back to Earth.

AUTONOMIC PROPERTIES

As this scenario clearly demonstrates, teams must have nearly total autonomy. The mission's nature will be constantly changing. More important, high latency—the delay due to signal propagation over large distances between Earth and the teams' location—as well as low bandwidth of communications to Earth will limit the availability and timeliness of information transfer between Earth and the mission. High latency reduces the timeliness and therefore usefulness of crucial information that could influence control decisions. Suppose a collision will occur unless the spacecraft takes avoidance measures within two minutes. If the round-trip signal propagation delay is 40 minutes, appropriate control decisions from Earth are impossible. Similarly, if the decision-making software requires more information than the spacecraft can transmit over the communications channel before a collision, the spacecraft would not survive. In both cases, giving the spacecraft the ability to modify operations

Figure 2. Individual ANTS spacecraft.



The tiny spacecraft that make up the swarm weigh only about three pounds each and fall into one of three classes: worker, ruler, or messenger. Two worker spacecraft carry different miniature instruments, customized for the mission (a). A ruler spacecraft (b) is primarily the operations planner and assigns workers to teams. The messenger (not shown) is similar to the ruler in appearance, but coordinates more of the communication within a team and between teams. The large square at the end of each craft is a solar sail, its primary source of propulsion.

autonomously would let it take the appropriate action in time to avoid the collision.

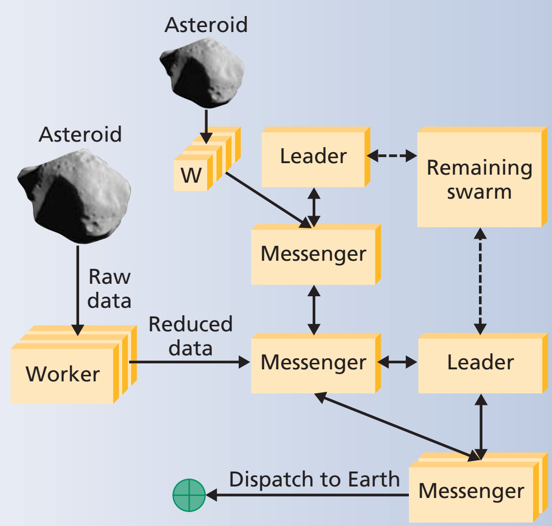
For ANTS exploration, individual autonomy is not crucial, but the mission cannot succeed unless each *team* has all the autonomic properties of being. There are four such properties, which by their nature do not have clear boundaries:

- *self-configuring*, able to adapt to changes in the system;
- *self-optimizing*, able to improve performance;
- *self-healing*, able to recover from errors or damage; and
- *self-protecting*, able to anticipate and cure intrusions.

Self-configuring

During the mission, ANTS' resources must be configurable to support concurrent operations at hundreds of asteroids. Resource application must consider the division of labor (among rulers, messengers, and workers), specialized worker operations, and cooperation among the spacecraft to achieve mission goals. Resources must support configuration at both the swarm and team levels. At the swarm level, the emphasis is on resource sharing and coverage of a particular region. At the team level, the emphasis is on coordinating science operations. These organizational levels evolve and must be able to self-configure as the need arises. When flybys first identify asteroids for investigation, teams must be able to self-configure to conduct the appropriate scientific experiments and measures. When the team completes those operations, it must be able to disperse and be available for reconfigura-

Figure 3. Team data gathering within the swarm.



Team workers send compressed data to their assigned messenger, which forwards it to the team leader. The leader might in turn forward data to a messenger coordinating with mission elements on Earth. A team messenger can also forward data to another team's messenger, which helps both teams obtain more accurate data about neighbors and about asteroid properties.

tion at another asteroid site. This configuring and reconfiguring continues throughout the ANTS mission.

With current and future hardware technology, designers could use reprogram devices, such as field-programmable gate arrays (FPGAs), to reflect reconfigurations automatically. System execution would then be faster, but it would also be flexible as the mission proceeds. Reconfiguration might also result from a failure or anomaly. A worker, for example, could collide with an asteroid, suffering hardware failure or complete destruction, which would require another worker to take over its tasks. Finally, communication devices on any class of spacecraft could fail, requiring other craft to assume new roles.

Self-optimizing

Self-optimization is important to mission efficiency and flexibility. Rulers self-optimize primarily through learning. Over time, they will collect data on many asteroid types and gradually improve their ability to discern the best asteroids for data gathering. They might be able to recognize, for example, an asteroid with a fast rotation, which would be difficult to orbit or to measure for data.

Messengers—which facilitate communications among rulers, workers, and mission elements on Earth—self-optimize through positioning. A messenger must constantly adjust its position to balance these communications, often maintaining communications between rulers and workers while attempting to send data to Earth.

Workers use their experience to self-optimize. As a worker observes more asteroids, it builds up a knowledge base of asteroid characteristics.

From optimization at the individual level comes system-level optimization, because the spacecraft do not waste time investigating asteroids that are difficult to investigate or irrelevant, thus optimizing mission exploration as a whole.

Self-healing

ANTS teams must be self-healing to recover from both mistakes and failures, including those caused by damage from an outside force. Damage can result from events such as collision with an asteroid or another satellite, and loss of connection—both of which will require the team to replace one spacecraft with another. Losing an instrument might also require a worker to become a messenger.

Scenarios requiring self-healing can range from negligible to severe. For example, a negligible scenario is one in which one member of a redundant set of gamma-ray sensors fails before the team can conduct a general gamma-ray survey. The self-healing behavior would be to simply delete the sensor from the list of functioning sensors.

An example of a severe scenario is when the team loses so many workers that it can no longer conduct scientific operations. The self-healing behavior could be to advise mission control a replacement worker is needed, to incorporate the replacement into the team, and perform any necessary self-configuration and self-optimization. Occasionally, instead of calling home, the ANTS team might request a replacement from another team or from a fielded repository of spares, orbiting nearby.

ANTS individual spacecraft might also have self-healing behaviors. It would be useful, for example, if an individual could detect corrupted code and self-heal by requesting a good copy of the offending code from another team spacecraft and using it to restore itself to an operational state.

Self-protecting

Self-protection must be at both the individual and team levels. The primary threats to ANTS individuals, and thus to the teams as well, are collisions and solar storms. Because individual spacecraft can maneuver only through thrust from solar sails, they will have limited ability to adjust their orbits and trajectories to avoid a collision. Given the chaotic environment of the asteroid belt and the highly dynamic trajectories of the objects in it, occasional near approaches of asteroids (even small ones) are very real threats. Individual spacecraft will have to self-protect through planning. The ruler's plans, for example, will be based on constraints that define acceptable collision risk.

Solar storms are another threat because charged particles can degrade sensors and electronic components. To protect against this threat, the ruler could be equipped with the ability to receive a warning message from the mission control center on Earth or to sense a solar storm itself. When the ruler recognizes a solar-storm threat, it would invoke its goal to protect the mission from harm. It might, for example, give workers the goal to protect themselves by orienting solar panels and sails to minimize the solar wind's impact or by powering down subsystems to minimize disruptions and damage from charged particles.

Typically, self-protection actions result in reconfiguration. After trimming their solar sails to mitigate the solar-wind blast, individuals might be on unplanned trajectories, which will necessitate trajectory adjustments, replanning, and perhaps the generation of new goals. The loss of spacecraft from damage by charged particles might also trigger ANTS self-healing and self-optimizing. In this way, the self-protecting behaviors of the team and individuals strongly interrelate.

SOFTWARE DEVELOPMENT WISH LIST

Developing the software for the ANTS mission will be monumentally complicated. The total autonomy requirement means the software will likely be based on a heuristic approach that accommodates the swarm's social structure. Artificial-intelligence technologies, such as genetic algorithms, neural nets, fuzzy logic, and on-board planners are candidate solutions.

But the autonomic properties, which alone make the system extremely complex, are only part of the challenge. Add intelligence for each of the thousand interacting space-

Resources

ANTS mission details

The following papers are available at http://ants.gsfc.nasa.gov:

- "ANTS: Applying a New Paradigm to Lunar and Planetary Exploration," P.E. Clark, S.A. Curtis, and M.L. Rilee, *Proc. Solar System Remote Sensing Symp.*, NASA Goddard Space Flight Center, 2002.
- "ANTS (Autonomous Nano-Technology Swarm): An Artificial Intelligence Approach to Asteroid Belt Resource Exploration," S.A. Curtis and colleagues, *Proc. Int'l Astronautical Federation, 51st Congress*, Int'l Astronautical Federation, 2000.
- "ANTS for the Human Exploration and Development of Space," S.A. Curtis and colleagues, *Proc. IEEE Aerospace Conf.*, IEEE Press, 2003, vol. 1, pp. 255-261.

Swarm behavior

- "Swarm Intelligence," G. Beni and J. Want, *Proc. 7th Ann. Meeting Robotics Society of Japan*, RSJ Press, pp. 425-428, 1989.
- "Self-Organization in Social Insects," E. Bonabeau and colleagues, *Trends in Ecology and Evolution*, vol. 12, 1997, pp. 188-193.
- "Swarm Smarts," E. Bonabeau and G. Theraulaz, *Scientific Am.*, Mar. 2000, pp. 72-79.
- "Formal Approaches to Intelligent Swarms," C. Rouff and colleagues, *Proc. IEEE/NASA Software Eng. Workshop*, IEEE Press, 2003, pp. 51-57.
- "Properties of a Formal Method for Prediction of Emergent Behaviors in Swarm-based Systems," C. Rouff and colleagues, *Proc. IEEE Int'l Conf. Software Eng. and Formal Methods*, IEEE CS Press, 2004.

Hardware and software support

- *Grid Computing*, J. Joseph and C. Fellenstein, IBM Press, 2004.
- "The NRL Micro Tactical Expendable (MITE) Air Vehicle," J. Kellogg and colleagues, *The Aeronautical J.*, vol. 106, no. 1062, 2002, pp. 431-441.
- "Onboard Science Software Enabling Future Space Science and Space Weather Missions," M.L. Rilee and colleagues, *Proc. IEEE Aerospace Conf.*, IEEE Press, 2002, pp. 2071-2084.

craft, and it becomes clear that the mission depends on several breakthroughs in software development.

Programming techniques and tools

A primary requirement is a new class of programming techniques and tools that either replace or build on object-oriented development. The idea is to reduce complexity through novel abstraction paradigms that would essentially "abstract away" complexity. Developers would use predefined libraries or components that have been solidly tested and verified. Programming languages would be at a high-enough level that developers could use constructs that are natural extensions to the software type under development.

Another requirement is tools and techniques that have built-in autonomic, intelligent, and interacting constructs to reduce development time and increase developer productivity. Tools must allow rapid simulation so that developers can identify requirements or code errors as soon as possible. For now, ideas about creating standard intelligent, autonomic components are still evolving, so there is no consensus as to what comprises a system of such components. Hopefully more research and development in these areas will yield useful results.

Verification

Testing software on the complexity scale of the ANTS mission seems impossible, but verification is critical because the spacecraft will be out of contact with ground control for extended periods. So there could be significant delays in detecting or correcting faults, which might cause a mission failure. For example, with so many communicating processes, race conditions are highly likely—but such conditions rarely come to light by inputting sample data and checking results. These types of errors are time based, occurring only when processes send or receive data at particular times or in a particular sequence, or after learning takes place. To find these errors, testers must execute the software in all the possible combinations of state space that communicating processes could be in. The number of these combinations is exponential and sometimes factorial to the number of states. Consequently, even with relatively few spacecraft, the state space is too large to test.

Thus, one of the most challenging aspects of using swarms is determining how to verify that emergent system behavior will be proper and that no undesirable behaviors will occur. Verifying intelligent swarms is even more difficult, because the swarms no longer consist of homogeneous members with limited intelligence and communications. Verification will be difficult not only because each individual is tremendously complex, but also because of the many interacting intelligent elements. To address the verification challenge, we are investigating formal methods and techniques for verification and validation of swarm-based missions using the ANTS mission as a case study. Formal methods are particularly useful in specifying complex parallel and distributed systems—where a single person finds it difficult to fully understand the entire system and where there are typically multiple developers. Testers can use a formal specification to prove that system properties are correct—for example, that the underlying system will go from one state to another or not into a specific state. They can also check for particular types of errors, such as race conditions, and use the formal specification as a basis for model checking.

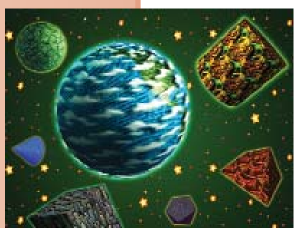
Most formal methods do not address the problem of verifying emergent behavior, however, which is an area that NASA is currently investigating. Clearly in the ANTS mission, the combined behavior of individual spacecraft is far more complex than each behavior in isolation.

Extending ANTS Technology Use

ANTS technology has many potential applications in military and commercial environments, as well as in other space missions. In military surveillance, smaller craft, perhaps carrying only a basic camera or other instrument, could coordinate to provide 3D views of a target. Indeed, the US Navy has been studying the use of vehicle swarms for several years.

In mining and underwater exploration, autonomous craft could go into areas that are too dangerous or small for humans. For navigation, ANTS technology could make GPS cheaper and more accurate because using many smaller satellites for triangulation would make positioning more accurate.

Finally, in other types of space exploration, a swarm flying over a planetary surface could yield significant information in a short time. In a few seconds, the craft could travel the distance it took the Mars rovers several months to cover. The ANTS technology could also benefit commercial satellite operations, making them both cheaper and more reliable. With its autonomic properties, a swarm could easily replace an individual picosatellites, preserving operations that are now often lost when satellites become damaged. Mission control could also increase functionality simply by having the swarm add members with the new functionality, rather than launching a new, complex satellite.



ANTS AND BEYOND

Although ANTS is still a concept mission, its underlying techniques and technologies are driving other NASA missions. Exploration missions to examine the rings of Saturn will use technologies strongly based on the ANTS concept. Similarly, a prototype tetrahedral walker that might one day explore the moon's rugged surface will likely use surface-based forms of ANTS technology.

ANTS is also motivating other technology and applications, as the "Extending ANTS Technology Use" sidebar describes. The obvious need for advances in miniaturization and nanotechnology is forging new groundbreaking advances at NASA and elsewhere. The requirement for power through solar sails is enhancing research in solar energy and battery technology. The ANTS mission also pushes the envelope in terms of current technologies for requirements engineering, nontrivial learning and planning, agent technology, self-modifying systems, and verification technologies. All in all, the paradigms, techniques, and approaches in the ANTS mission hold much promise for future space exploration missions: large numbers of small spacecraft provide greater flexibility, reliability, and autonomy than the more familiar large spacecraft.

Although much of this work might seem daunting or even far-fetched to some, technology is evolving to meet the challenges. The reward for hard-fought research will be a new level of complex software systems for use not only in space exploration but also in a variety of commercial and military applications. ■

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